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Maneuvering aircraft operate in rapidly changing, time-dependent flow fields and it is well established that certain predictable and controlled unsteady flows enhance aircraft maneuverability. However, any attempt to apply unsteady flow mechanisms to flight vehicles must be preceded by thorough analysis of the basic fluid dynamics of unsteady leading edge and wingtip vortics. This study focuses on the vortex-vortex interactive region produced on a rectangular wing when oscillating through sinusoidal motions about the quarter chord. Phase-locked, stroboscopic photographic flow visualization shows repeatable patterns of leading edge and wingtip vortex size, development, position and convection velocity throughout the pitching cycle. These dynamic fluid characteristics are confirmed and partially quantified using hotwire probe velocities and surface pressure measurements. A representative sampling of the data is presented along with the hypotheses formed and confirmed during the three investigations. Keywords: Pitch motion;

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VORTEX FLOWS CREATED BY SINUSOIDAL OSCILLATION OF THREE-DIMENSIONAL WINGS

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Abstract

Maneuvering aircraft continuously operate in the regime of rapidly changing, time-dependent flow fields and it is well established that certain predictable and controlled unsteady flows enhance aircraft maneuvering capability. However, any attempt to apply unsteady flow mechanisms to inflight vehicles must be preceded by a thorough analysis of the basic fluid dynamics of unsteady leading edge and wingtip vortices. This study focuses on the vortex-vortex interactive region produced on a rectangular wing when oscillating through sinusoidal motions about the quarter chord. Since flow visualization permits initial qualitative investigation of complex flow structures, phase-locked, stroboscopic photography was utilized for initial data collection. Quantitative data were collected using hotwire anemometry and surface pressure measurements. The flow visualization analyses across the span of the wing show repeatable patterns of leading edge and wingtip vortex size, development, position and convection velocity throughout the pitching cycle. These dynamic fluid characteristics are confirmed and partially quantified using hotwire probe velocities and surface pressure measurements. A reasonably thorough analysis of this phenomenon is now feasible. A representative sampling of the data is presented along with the hypotheses formed and confirmed during the three investigations. These experiments provide an initial data base for comparison and validation of computational codes for the prediction of force and moment information about a dynamic control surface.

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Nomenclature

c	Wing chordlength (6 inches)
C	Nondimensional chord position measured from the wing leading edge (distance/c)
Cn	Force coefficient normal to the chord line
k	Nondimensional reduced frequency parameter, $k = \omega c/2V_\infty$
S	Nondimensional spanwise distance from the wingtip (distance/c)
V	Local absolute velocity measured at the hotwire probe position
V_∞	Freestream velocity
α	Instantaneous geometric angle of attack (degrees)
α_m	Mean angle of attack (degrees)
α_ω	Oscillation amplitude (degrees)
Φ	Nondimensional oscillation phase angle (% cycle)
ω	Rotational frequency in radians per second

Introduction

To fully comprehend the flight characteristics and maneuvering potential of agile aircraft in an air-to-air environment, we must understand the unsteady phenomena affecting these highly dynamic vehicles. Control surface forces and moments in this unsteady environment depend on vortex production, strength, loiter time on the wing and vortex-vortex interactions. Omission of vortex dynamics from the analysis of these dynamic flows would lead to erroneous predictions that could cause catastrophic results. Incorporation of unsteady aerodynamic technology into advanced aircraft design can be achieved only after complete understanding of the effects of unsteady flow fields. The nature of most physical flows is very predictable, however, a wide data base is essential for the computational prediction of flows about even more agile maneuvering aircraft.

The current technology of computational techniques[1-5] provides a prediction capability that was unattainable only a few years ago. However, even now, code validation requires comparison with some verified quantity of reliable experimental data. Experimental results on unsteady flow fields about two-dimensional airfoils began with investigations in rotor blade aerodynamics[6] and progressed into possible lift enhancement studies[7-9]. Since operational wings are necessarily three-dimensional, the unsteady flow studies continued into three-dimensions including oscillating motions[10-15], accelerating flows[16] and high rate pitching motions[17-22]. Also, experimental investigations[23-24] into the feasibility of applying unsteady flow technology to actual aircraft appear promising. The investigation discussed here explores the intricate flow patterns of and provides insight into the three-dimensional flow characteristics of the leading edge and wingtip vortex interactive region on a pitching wing.

This analysis combines flow visualization, hotwire anemometry and surface pressure measurements to define the unsteady flow field and vortex-vortex interaction. The qualitative flow visualization data was recorded using a smoke wire technique. This data illustrates the position and size of the leading edge and wingtip vortices throughout the pitching cycle. Hotwire measurements above the upper wing surface provide quantitative velocity measurements across the chord and span of the wing. Since the hotwire probe positions must be above the oscillating wing, and since the directionality of unsteady flows vary, surface pressure measurements are necessary to more accurately quantify the flow affecting the wing. The pressure data indicate the vortex position and the magnitude of the surface velocities as well as how their characteristics change throughout the pitching cycle. The upper and lower surface pressure distributions are integrated to give the cyclic normal force coefficient history. This data base will aid the computational integration required for aerodynamic prediction of the forces and moments produced by three-dimensional unsteady flows.

Methods

Initial flow visualization and hotwire data were taken in the 16 X 16 inch, low speed wind tunnel at the University of Colorado. The tunnel velocity was set to maintain a Reynold's number of 40,000 based on the wing chordlength. The Plexiglas wind tunnel side wall and top allow orthogonal-view, flow visualization. The wing was constructed from a NACA 0015 airfoil section with a flat endplate fashioned to the airfoil shape. The wing was mounted horizontally from the side wall of the tunnel and was oscillated about the quarter chord line. The frequency of the sinusoidal oscillations was set to maintain a reduced frequency, k, of 1.0. The mean angle of oscillation was 15^{o} and the oscillation amplitude was $\pm 10^{o}$. During the flow visualization tests, a 35mm camera and phase-locked stroboscopic (10 usec duration) flash unit were used to record the multiple exposure photographs[11-13]. A smoke wire suspended between top and bottom of the tunnel was used to produce vertical smoke sheets at the desired span location of the each wing. Spanwise investigations were conducted by positioning the smoke wire at different intervals along the span of the wing.

Hotwire anemometry data was recorded at dynamic conditions identical to the flow visualization investigations. The hotwire probe was positioned in a horizontal plane 1/4 inch above the quarter chord of the wing to avoid contact with the wing during the pitching motion. Seven equally spaced chordwise positions were tested from the leading edge to the trailing edge. The spanwise probe locations were identical to those used for the flow visualization data. Velocity data for ten complete pitching cycles were computer averaged and plotted. Each run collected over 200 temporal data points and plotted the average velocity trace for ten cycles. Data were compared to the tunnel freestream velocity. The pitching cycle begins with the wing at the maximum angle of attack.

Surface pressure data was collected with the wing in the Frank J. Seiler Research Laboratory 3 X 3 foot low speed wind tunnel at the United States Air Force Academy. The data was recorded using 15 surface mounted pressure transducers on one side of the wing. Complete surface data was obtained by inverting the wing and reversing the direction of oscillation. The wing is equipped with interchangeable wingtip lengths to allow a spanwise investigation of the pressure distribution. The data was collected, digitized, and stored using a Masscomp 5500 data acquisition system. The data acquisition equipment and calibration technique are discussed in detail elsewhere[20]. The pressure port locations and model schematic are shown in Fig. 1. The data is presented here as time-dependent pressure contour plots and normal force coefficients for each wing span location.

Results

Complete analysis of the unsteady flow fields about three-dimensional wings must include both qualitative and quantitative results. For all data collection, static tests were conducted as a baseline condition for comparisons with

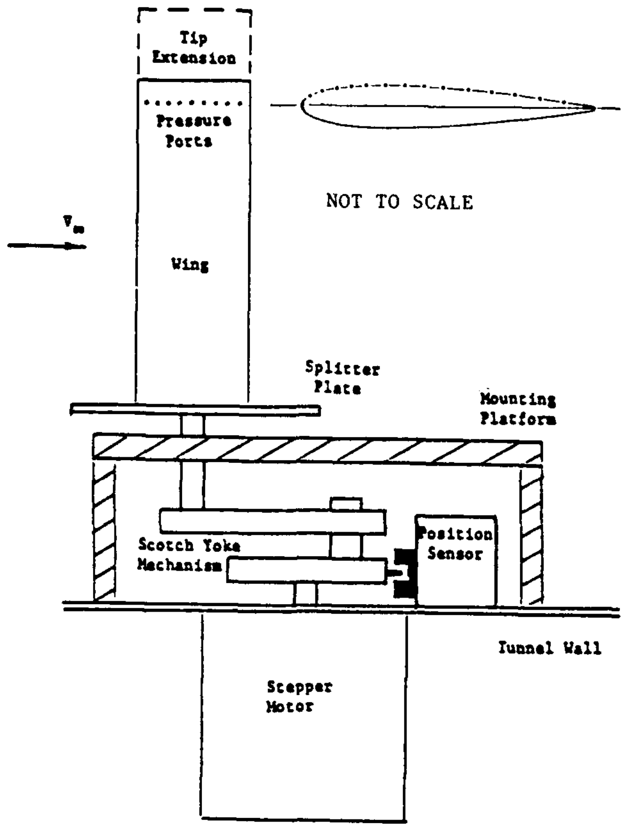

Fig. 1. Model Schematic and Pressure Port Location

the dynamic (sinusoidal oscillation) data. The flow visualization technique determined the position and size of the vortex formations throughout the pitching cycle. The leading edge and wingtip vortex effects and interactions were recorded. Quantitative data included hotwire velocity measurements. The velocity fluctuations readily indicate the cyclic position and magnitude of the unsteady vortices. The surface pressure data also indicate the position and transient passage of the vortices as well as the nature of existing vortex-vortex interactions. All three data collection techniques must be utilized to fully define the flow.

Flow Visualization

A spanwise visualization of the leading edge and wingtip vortices produced about the wing at $\phi = 0.3$ is shown in Fig. 2. With the smoke sheet introduced at the wingtip, S = 0.00, a dominant wingtip vortex is observed. At S = 0.33, the flow above the wing appears attached with a shear layer present on the surface of the wing. As more inboard locations are investigated, S = 0.5, a leading edge vortex is forming with the vortex center near the quarterchord. The size of the leading edge vortex increases with inboard location and reaches a maximum at S = 1.00. As the more inboard locations are examined, the leading edge vortex size diminishes. These photographs show the spatial characteristics of the leading edge and wingtip vortices across the span of the ing.

To illustrate the size and convective characteristics of the leading edge vortex, Fig. 3 shows flow visualizations for a complete pitching cycle in 10% increments at S = 0.67. At the maximum angle of attack, $\phi = 0.0$, the shear layer vorticity is coalescing into distinct vortex patterns. At $\phi = 0.2$ and 0.3, a large leading edge vortex is observed near the leading edge and a secondary vortex is seen downstream near the midchord position. As the cycle continues to pitch the wing toward the minimum angle of attack, $\phi = 0.3$ to 0.5, the leading edge vortex becomes less distinct and is pushed toward the trailing edge by the freestream flow. From $\phi = 0.6$ to 0.9, the leading edge vortex is shed from the trailing edge and the flow reattaches to the surface of the wing.

To illustrate the chordwise and spanwise location of the leading edge vortex for the first half of the pitching cycle, a planform view of the wing is shown in Fig. 4. The leading edge vortex positions are shown at $\phi = 0.0$, 0.25 and 0.5. The leading edge vortex convection is retarded near the wingtip, and, the vortex core positions seem to focus at an apex near the leading edge at the wingtip[11,20].

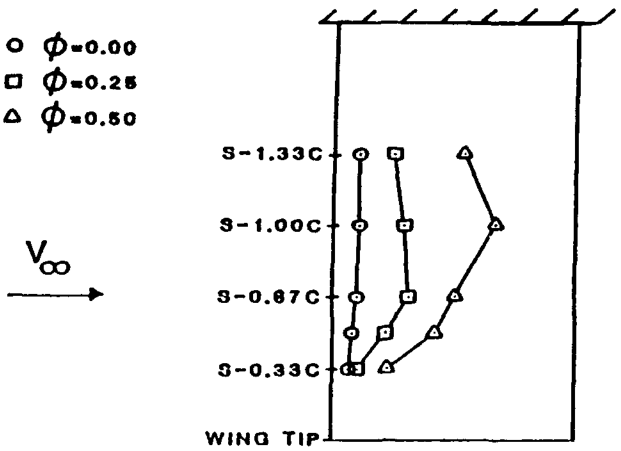

Fig. 4. Planform of Leading Edge Vortex Position, k = 1.0

Hotwire Anemometry

Hotwire velocity profiles for two complete pitching cycles of the wing are shown in Fig. 5. Four spanwise locations are shown to illustrate the velocity differences due to span location. The hotwire probe is located at C = 0.17 to capture the velocity fluctuations associated with the formation and convection of the leading edge vortex.

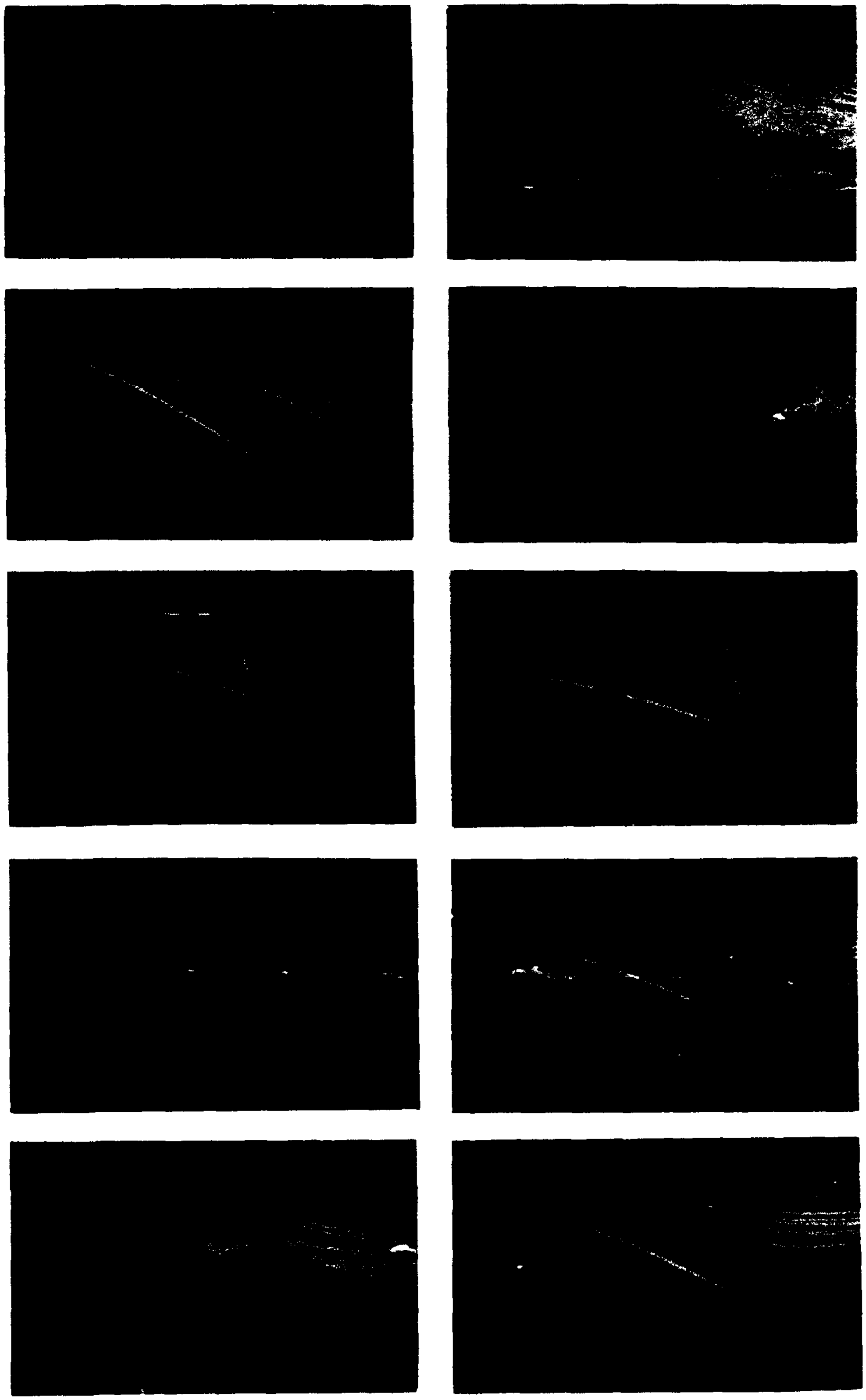

Fig. 3. Photographic Comparisons Over One Pitching Cycle, $k = 1.0$, $S = 0.67$

S = 0.00

S = 0.17

S = 0.33

S = 0.50

S = 0.67

S = 1.00

S = 1.33

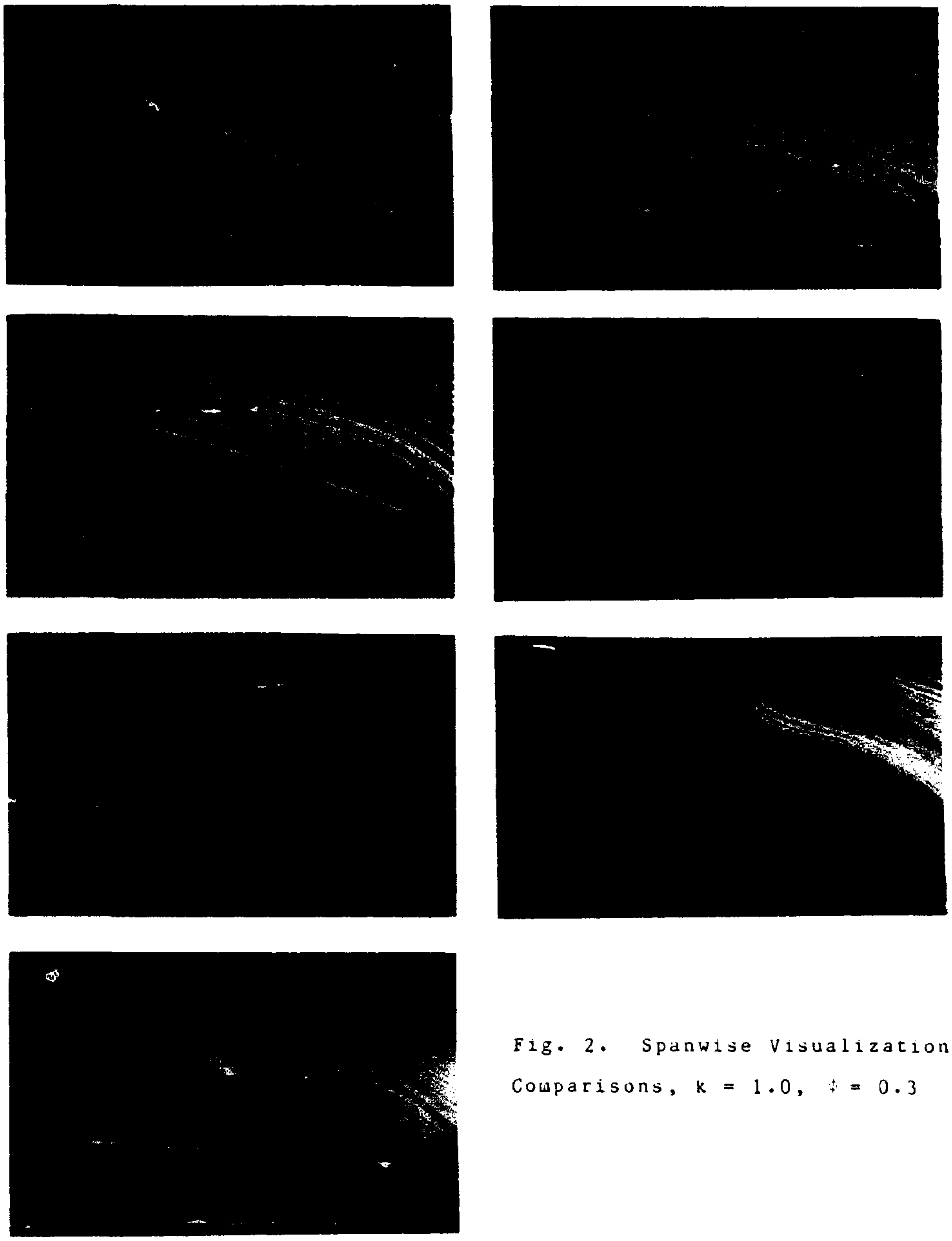

Fig. 2. Spanwise Visualization Comparisons, k = 1.0, ϕ = 0.3

Velocity profiles at other chord locations show less pronounced fluctuations in the regions of more diffuse vortex structures. The higher velocity peaks are coincidental with the circumferential velocities of the passing leading edge vortices and the lower measured velocities are indicative of the vortex inner core passage. Near the wingtip, S = 0.00, the velocity fluctuations are due to the wingtip vortex and are not as significant as at the more inboard locations where the leading edge vortex is dominant. At the next inboard position, S = 0.33, the probe records the peak velocities associated with the circumference and core of the leading edge vortex. The probe appears to sense the upper portion of the small, cohesive leading edge structure. Further inboard, S = 0.67 and 1.00, the probe senses the circumferential and core velocities of a large, cohesive leading edge structure. Early in the pitching cycle, ϕ = 0.0, the hotwire probe records the high velocities of the circumference of the initiating leading edge vortex. As the vortex forms, the core is located at the probe position and the local velocities are quite low at the center of the vortex, ϕ = 0.25. As the vortex convects across the surface of the wing, the probe records the velocity recovery to the freestream and higher value associated with the flow reattachment observed in the flow visualizations for ϕ = 0.4 to 0.9. At the beginning of a new pitching cycle, ϕ = 1.0, the local velocity is again at a peak value.

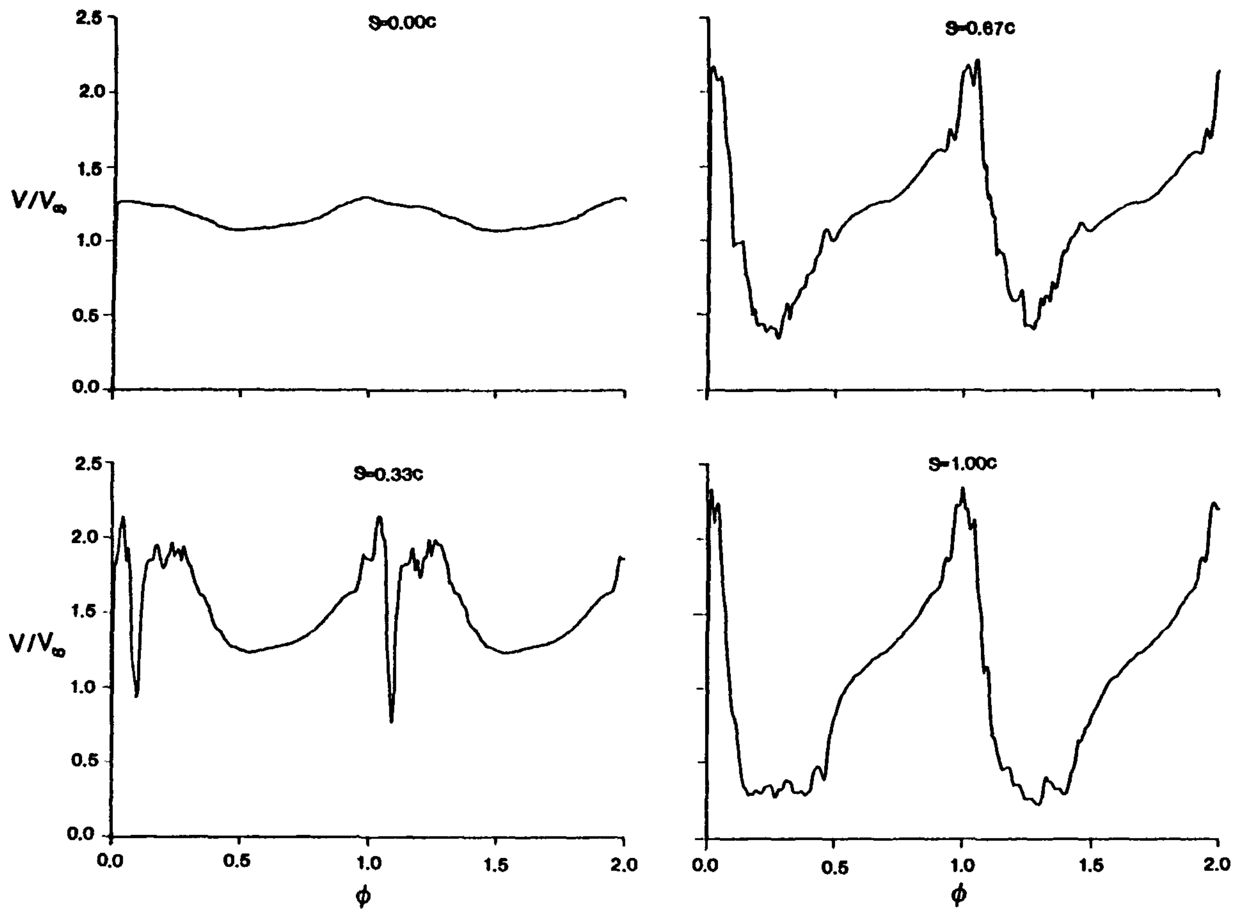

Fig. 5. Velocity Profiles Across Span, k = 1.0, C = 0.17

Surface Pressure

Pressure data collected on the surface of the wing confirms and quantifies flow characteristics observed with the previously discussed experimental techniques. Surface pressure measurements at the spanwise pressure port locations are recorded throughout the pitching cycle and multiple runs are averaged to obtain the plots. The pressure coefficient data for two reduced frequency values of 0.6 and 1.0 are shown in Fig. 6. The pressure coefficient peaks shows the high values associated with the passage of cohesive vortex structures. Therefore, the vortex strength and position can be traced across the chord and span of the wing by observing the pressure coefficient distribution for complete cycles of the pitching motion.

At span location S = 0.4 for the k = 0.6 data, high cyclic peaks in the pressure profiles near the wing leading edge indicate the presence of the leading edge vortex. Downstream from these peaks, the absolute value of the pressure coefficient decreases. At this span location, no surface convection of the leading edge vortex is indicated since the pressure ridges do not move to the right in the data plot as the pitching cycle progresses. The peaks occur at repeatable intervals in the cycle coincident with the passage of vortices as observed during flo visualization tests. At S = 0.6, the plotted pressure peaks remain high over more of the chordlength indicating the pressure of larger vortices that encompass more of the forward wing surface. Again, very little surface convection is observed. At S = 0.8, the peak in plotted pressure coefficient occurs aft of the quarterchord position. A slight shift in the pressure ridge indicates some vortex convection, however, only insignificant pressure fluctuations are noted at the trailing edge. The highest pressure peaks are observed at S = 1.0 and are located nearly at the midchord position. Some convection is noted by the shift of the plotted pressure ridge, but only a small pressure peak is recorded at the trailing edge. More inboard positions, recorded but not shown, indicate smaller pressure peaks, more shift in the pressure ridges and higher peaks at the trailing edge.

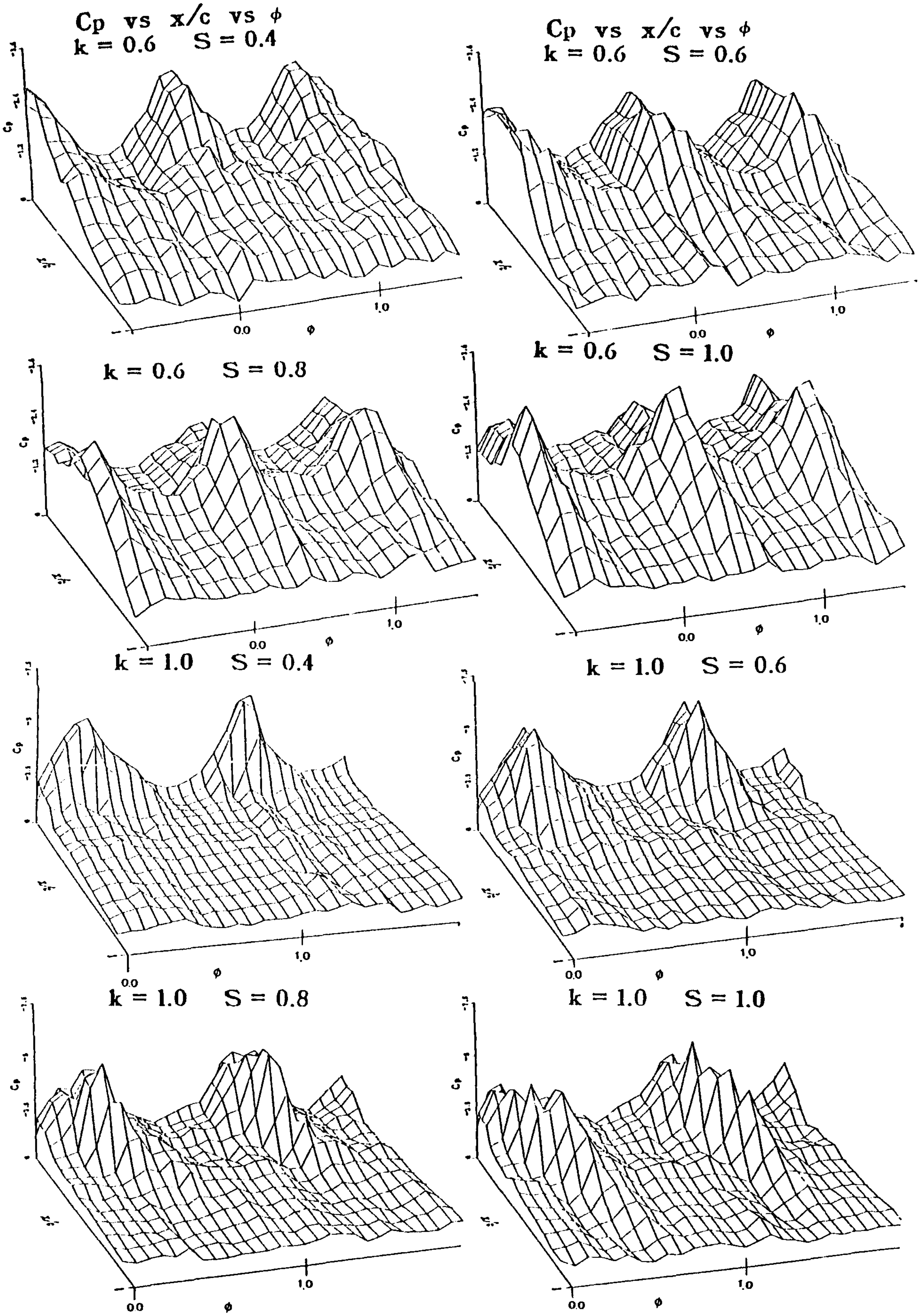

Fig. 6 Pressure plots

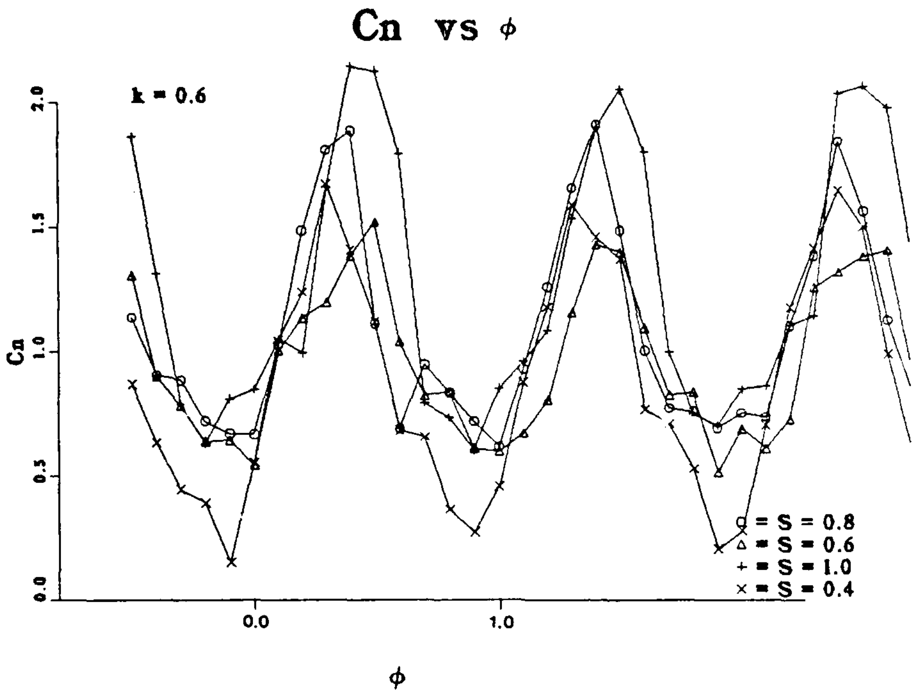

Fig. 7. Normal Force Coefficients, k = 0.6

The k = 1.0 data (note the scale change on the pressure coefficient axis) show higher peaks in the pressure coefficient data. At the S = 0.4 position, the peaks are very high and are confined to the most forward portion of the wing chordlength. No convection is observed and the coefficient data remains reasonably constant across most of the chordlength throughout the pitching cycle. As more inboard positions are examined, the pressure peaks encompass more of the wing surface and shift aft on the chord. At S = 0.8 and 1.0, more vortex convection is noted by the shift in the plotted pressure ridge as the pitching cycle progresses.

As a comparison of cyclic forces produced by these unsteady flows, Fig. 7 shows the variation of normal force coefficient with pitching cycle. The four traces are for different span locations at k = 0.6. These plots show maximum and minimum values for each span location at nearly the same point in the pitching cycle. The normal force coefficient fluctuations are greater for the S = 0.4 than for the S = 0.6 but the greatest variations occur at S = 1.0. The mean value of the force coefficient at S = 1.0 is approximately 1.3. The mean value increases with more inboard span location. The relative magnitudes of the k = 1.0 data show the same trends as the k = 0.6 data. The maxima and minima of the fluctuations for the k = 1.0 data are greater, as predicted by the pressure coefficient plots.

Discussion

The three data collection techniques of flow visualization, hotwire anemometry and surface pressure measurements each illustrate characteristics of an unsteady flow field. In combination, these investigations define and verify hypotheses which can lead to a complete understanding of the flow about an oscillating planar wing. The location, size and velocity of the leading edge vortex and the resulting pressure distribution about the wing can now be discussed. The effect of span location on these quantities is also known.

The flow visualization experiments provided the initial qualitative data on the unsteady flow field about this wing. The leading edge vortex forms during the high angle of attack phase of the pitching cycle and coalesces into a cohesive structure near the leading edge of the wing. As the cycle progresses, the vortex becomes larger and then less distinct as it moves toward the trailing edge of the wing. The leading edge vortex size was dependent on proximity to the wingtip and the wingtip vortex. The leading edge structure was small near the wingtip and larger near the S = 1.0 position. Further inboard, the size decreased with span location. Near the wingtip, the leading edge vortex showed little, if any, tendency to traverse across the wing surface. Further inboard, this vortex was larger and demonstrated more convection tendencies but was less distinct as it passed toward the trailing.

The hotwire data confirmed the position of the leading edge vortex on the wing and allowed quantitative analysis of the flow. Large velocity fluctuations were observed when a small, cohesive vortex was formed in the vicinity of the probe position. As other investigations have shown[7,13], the velocities in the circumference of the vortex were large compared to the velocities in the core. The probe velocities at the wingtip were smaller than those seen further inboard because the probe was near the core of the wingtip vortex. A limitation of the hotwire probe was the single wire which could not record velocity direction but only magnitude. The probe was also limited to a position above the oscillating wing which would avoid physical contact with the wing during the motion.

The surface pressure measurements allow further quantification of the flow field. The effects of vortex position and velocity on the wing are plotted as a variation in surface pressure coefficient. Near the wingtip, the small leading edge vortices were shown to be strong and produce large pressure coefficient peaks. These small structures may not have been sensed by the hotwire probe due to the probe height above the wing. The pressure data confirmed the presence of the larger vortices at more inboard locations and associated smaller velocities during vortex convection phase. The inboard vortex structures also showed more convective tendencies than those near the wingtip. The pressure coefficient data was dependent on the reduced frequency of oscillation. As k was increased, the magnitude of the pressure coefficients also increased. The normal force coefficients were higher near the root and increased with reduced frequency.

Conclusions

This investigation may provide insight into the application of forced unsteady flows. From the data collected using the three techniques, we can see that the smaller, forming vortices near the leading edge produced greater peak velocities but affected a smaller area of the wing and thus produced overall smaller force coefficients over the wing. The larger, more inboard leading edge vortices affected more wing area and showed greater convective tendencies during the pitching cycle.

Maneuvering aircraft necessarily operate in an arena of unsteady flows,and understanding and controlling these flows can enhance aircraft agility. One of our experimental aircraft, the X-29, produces an unsteady flow about the canard as it moves 40 times per second to maintain stable flying characteristics. Pressure peaks are observed near the leading edge of the canard as it goes through pitching motions[25]. Controlling this unsteady phenomenon for lift enhancement may be feasible on future aircraft.

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